REDUCTION OF ICE PARTICLE PRODUCTION FROM

MOIST PLUMES

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W.G. Nelson

William G. Nelson

Associate Professor Mechanical Engineering

University of Alaska, Anchorage

Anchorage, Alaska 99504

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- A B S T R A C T -

It is generally conceded that the major effect of ice fog is the impairment of visibility. After a review of the physics of ice fog formation, the author, suggests methods to reduce the visibility reduction caused by various sources and, discusses several experimental attempts to reduce wet plume condensation and to increase the size and reduce the number of nucleated droplets within the plumes.

This discussion of the physics of ice fog formation includes modes of nucleation, growth, and freezing of droplets in wet plumes subjected to cold ambient air. The effect of ambient temperatures and various plume physical properties including temperature, water vapor content, plume-ambient air mixing rates, and plume outlet diameter and velocity are discussed.

The experimental attempts to reduce ice particle generation are compared to predictions based upon the author's work in modeling ice particle nucleation and growth in automobile exhaust plumes.

INTRODUCTION

Ice fog continues to be a major low temperature air pollution problem in northern regions. Fairbanks, Alaska provides a good example of the occurrence of ice fog in populous regions with visibility reported in city blocks during ice fog episodes. The physical properties of ice fog in this region have been well documented by the work of Benson[1] and Ohtake[6]. As typical of northern regions, the primary producers of ice fog in the Fairbanks area include automobiles, trucks, power plants, and home heating plants. In addition, where available, open cooling ponds are excellent sources of ice particles. Their production of conventional fog has been well documented by Currier[2].

The size and quantity of ice paticles produced are a function of the physical properties of the plumes as well as the ambient temperature. Measurements by Ohtake in the Fairbanks area indicate that particulate produced at ambient temperatures of about -40°C from auto exhaust plumes have a mean diameter of approximately two micrometers. Ice particles produced above open water surfaces are larger with mean diameters of about twelve micrometers. This value agrees quite well with that of 7.5 to 10 micrometers reported by Currier for water droplets in fog over cooling ponds.

The onset of ice fog at a particular location is a function of the number, physical properties and size of moist plumes. In addition, of course, the temperature, water vapor content, and mixing capability of ambient air are extremely important. Ice fog in the Fairbanks area generally occurs at temperatures below -30°C. The maximum ice fog occurrence temperature is increasing annually with the increase in water vapor sources due to an increasing population.

The purpose of this paper is to review the physics of ice fog formation, suggest methods to reduce the ice particle production from moist plumes and, to some extent, review and suggest experimental attempts to reduce the production of ice particles from moist plumes.

PHYSICS OF ICE FOG FORMATION

Although the visual properties of ice fog and conventional fog are similar, ice fog particles may be formed by different mechanisms.

Ice fog particles, when viewed under high magnification, resemble frozen water droplets. Ice fog particles are formed by the nucleation and growth of a droplet with subsequent freezing and growth of the droplet. Unlike natural fog which nucleates and grows at relative humidities

approaching 100%, ice fog droplets may nucleate and grow within plumes whose relative humidity may reach 600%. This extreme humidity allows droplets to form by nucleation on solid particles and self-nucleation as well as nucleation on salt particles.

Ice fog particles are generated when relatively warm moist plumes exit into cold ambient air with subsequent mixing of the cold air into the plume. Upon mixing of the air and plume two competing actions take place. With the introduction of the relatively dry ambient air the concentration of water vapor within the plume decreases, tending to discourage droplet formation. Concurrently, the cold ambient air decreases the temperature of the plume. This tends to encourage droplet formation.

Basic energy and mass balance computations are utilized to quantify the above effects and to determine which effect controls. Relative humidities of approximately 100% are necessary before droplet nucleation can begin. An example of the above described competing effects is seen in even moderately warm temperatures. Many times an auto, during early stages of operation on a cool day, exhibits a visible condensation plume. When the exhaust system warms up the condensation plume disappears. This is so because during the early stages of operation the exhaust plume is cooled by the cold exhaust system. As it exits into the cool ambient air the cooling effect increases the saturation ratio within the plume to that necessary for droplet formation. After the auto exhaust system is warmed, the exhaust exits into the ambient air at a higher temperature. Now it takes more ambient air to lower the plume temperature. The plume is sufficiently diluted before reaching the required low temperature so that the saturation ratio is not sufficient to initiate droplet nucleation. In this example only the plume exit temperature is changed to decrease or eliminate droplet nucleation.

The mechanics of the formation of ice particles within a moist plume can be described as follows:

1) The moist plume exits into the low temperature ambient air.

2) The low temperature ambient air mixes with the warm moist plume lowering the plume temperature and diluting the moist plume with relatively dry air.

3) If the dilution effect limits the saturation ratio to values well below unity there is no droplet nucleation.

4) If the saturation ratio within the plume approaches unity, droplet nucleation commences on hygroscopic salt particles contained in the original plume and those introduced into the plume with the ambient air.

5) If the saturation ratio within the plume reaches approximately two, droplet nucleation upon nonsoluble particulate within the plume may commence. (The exact saturation ratio necessary is a function of the insoluble particle size, shape, and surface properties.)

6) A saturation ratio of approximately four is necessary before droplets can form without a nuclei to form upon.

7) The self nucleated droplets and those nucleated on soluble particles and insoluble particles continue to grow as long as the partial pressure of water vapor surrounding them is greater than the vapor pressure of the curved droplet solution.

8) The saturation ratio within the plume is a function of, a) the mixing ratio of ambient air and plume gases, b) the initial water vapor content within the plume and ambient air, c) the initial temperature of plume and ambient air and d) the rate of growth of the droplets within the plume. Factors tending to lower the saturation ratio within the plume include dilution with ambient air and condensation of water vapor onto droplets or ice particles.

9) Given droplet nucleation within the plume the droplets will then grow, shrink, or remain stable depending upon the saturation ratio of their immediate environment.

10) Upon cooling of the droplets to temperatures below 0°C, they will change from liquid to ice. The exact freezing temperature is a function of the droplet solution, possible ice nucleating agents within the droplet, and droplet size. For example, from thermodynamic considerations Fletcher[3] predicts a freezing temperature of -40°C for a one micrometer diameter water droplet with no impurities. A similar sized droplet containing an ice nucleating agent will freeze at about 0°C.

11) Ice particle growth and stability upon freezing is enhanced by the reduction of the vapor pressure over ice with respect to that of water.

12) Ultimately the plume is completely diluted and the produced ice particles are suspended in the ambient air with settling velocities dependent upon their size and shape. At this point their long term size stability is a function of the relative humidity of the ambient air.

SUGGESTED PLUME MODIFICATIONS TO REDUCE ICE PARTICLE PRODUCTION

Several authors including Coutts[3] and Nelson[5] have reported on theoretical and experimental methods to reduce or eliminate ice particle production from moist plumes exiting into low temperature ambient air.

The most direct method is to remove the water vapor from the plume before it exits into the cold air. Possible methods include the use of condensers, as reported by Coutts for auto exhaust, dehydration apparatus, and fuel modification. Condensers offer a good potential in that heat rejection to ambient air from exhaust, which is necessary for condensation of the water vapor, is enhanced at low temperatures where the ice fog problem is greatest. Dehydration apparatus have been used with some success on power plant stacks. These methods have long been utilized for dehydration of natural gas in the petroleum industry and should see greater use for

water vapor control in the arctic. In implementing water vapor removal operations in cold climates expected low temperature problems have been encountered which include ice formation in the condenser and condensate removal sections and condenser water disposal problems. For large scale operations the disposal of the polluted condensate in northern regions results in a land or water pollution problem. In addition, depending on the process, severe corrosion problems may be encountered increasing the expense of the condenser and condensate handling equipment.

Fuel modification, where applicable, offers a solution. One can effectively lower the mass of water vapor exhaust per unit time by employing a fuel which produces a smaller amount of water vapor per unit of energy. An example might be a conversion to coal from natural gas resulting in more than a tenfold decrease in water vapor emitted per unit or produced energy.

From an analysis of the physics of ice particle formation other methods of decreasing ice particle formation suggest themselves. Included among these methods are an increase in the exit temperature of the plume and an increase in the initial plume diameter. These methods suggest themselves based upon the strategy that the saturation ratio within the plume should be minimized during the droplet nucleation and growth period. As noted earlier, minimum saturation ratios of about one, two and four are necessary for droplet nucleation on soluble particles, insoluble particles, and for droplet nucleation without a nuclei. To date, little work has been done to test this concept.

Numerical work by Nelson showed that ice particle production could be greatly reduced by increasing the temperature of a moist plume exiting into cold ambient air. Preliminary computations indicate a measureable reduction in ice particulate formation can be achieved by insulating or shortening conventional automobile exhaust systems. This concept will be tested during the winter of 1979-1980.

CONCLUDING REMARKS

The focus of this work is to suggest methods to reduce the number of ice particles produced by a moist plume exiting into low temperature ambient air. The most important and most controllable factor which relates to the number of ice particles produced is the saturation ratio. If the saturation ratio reaches unity, droplet and ultimately ice particles can form on salt nuclei contained in the plume and in the mixed ambient air. Higher saturation ratios will result in faster growth rates of the nucleated droplets. As saturation ratios increase above approximately two, one will see droplets nucleated on insoluble particulate and for yet higher saturation ratios droplets may form without nuclei. This results in a larger number of ice particles which cause a greater decrease in visibility.

Methods suggested to reduce ice particle production then, include those that will minimize saturation ratios within the plumes thus resulting in fewer produced ice particles. The resulting produced ice particles, being fewer in number, could very well be larger in size. This is an advantage in that their settling velocity will be higher with little incremental decrease in visibility.

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NELSON, William G.
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